Characteristics of Raindrop Throughfall Under Corn Canopy

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ABSTRACT

A laboratory rainfall simulator was used to study the raindrop size and velocity under a corn canopy. Drop sizes were measured by using a dye-paper technique, and drop velocities were measured photographically. Stemflow was calculated on the basis of rainfall under the canopy and incident rainfall above the canopy.

Up to 49% of incident rainfall appeared as stemflow. Drops that directly penetrated the crop canopy accounted for much of the throughfall kinetic energy; drips from leaf margins also contributed greatly to throughfall kinetic energy. Drops that splashed from leaves were quite small and contained little kinetic energy.

The ratio of the kinetic energy at ground level to kinetic energy at the top of the canopy was compared with the ratio predicted by Wischmeier and Smith (1978) for use in the Universal Soil Loss Equation. The comparison indicated little difference between what we observed and that predicted.

INTRODUCTION

A better understanding of the drop size and drop velocity characteristics of rainfall passing through crop canopy (throughfall) is needed to estimate throughfall erosivity (kinetic energy) and to test the assumptions upon which the canopy subfactor model of the Universal Soil Loss Equation (USLE) is based. The canopy subfactor is the ratio of rainfall erosivity (KE) with a crop canopy to rainfall erosivity without a crop canopy. The canopy subfactor is one of three subfactors multiplied together to estimate the cover and management factor (C) of the USLE, an index related to the effect of crop cover and management practices on soil erosion (Wischmeier and Smith, 1978).

The canopy subfactor model determines subfactor values for various combinations of canopy cover and average raindrop fall distance from leaf margins (Wischmeier, 1975). Assumptions implicit in the model are:

1. The percentage of rainfall intercepted by canopy is equal to the percentage of the ground surface covered by canopy.
2. The erosivity of intercepted rainfall is equal to the energy of 2.5-mm drops falling from an average leaf margin elevation.
3. Erosivity increases due to drop coalescence are offset by erosivity lost in stemflow.

The erosivity of throughfall may be underestimated where the erosivity of coalesced drops falling from leaf margins exceeds the erosivity of the drops from which they formed (Schottman, 1978). Since the canopy subfactor model does not allow for stemflow the erosivity of throughfall could also be overestimated. The objective of this study was to determine the effect of canopy on throughfall erosivity and compare this effect with that estimated using the USLE canopy subfactor model.

REVIEW OF LITERATURE

The effect of canopy on rainfall erosivity has interested researchers for some time. Haynes (1940) observed that both the kinetic energy and the total quantity of throughfall decreased when he contrasted the characteristics of throughfall under drilled corn with that under row corn. He also found a more uniform volume distribution of throughfall under the drilled corn canopy. Rainfall interception decreased during a storm because canopy decreased as leaf surfaces became wetter and heavier. Stemflow accounted for up to 22% of total precipitation for corn planted with a row spacing of 1050 mm and with 230 and 350-mm plant spacings along the row.

Chapman (1948) reported that at intensities greater than 50 mm/h, the kinetic energy of throughfall under a pine forest was greater than that in an open field. A more uniform distribution of drop sizes occurred under the pine canopy, and there was a greater percentage of large drops. Chapman reasoned that water did not fall from the margins of the pine canopy until the drops attained a certain size. Schottman (1978) predicted that drop coalescence could form crops of considerable erosivity, depending on the height of fall. Some coalesced drops needed to fall no further than 1.0 m to regain the erosivity of the smaller drops from which they had formed.

Kitanosono (1972), using photographic techniques, observed that raindrops striking a tobacco leaf were affected by the position of impact on the leaf, the angle of inclination of the leaf, the condition of the leaf surface, and the impact angle between drops and leaf. He noted that drops striking the central vein of the leaf spread on the leaf without splashing; other drops striking the leaf broke into 25 to 30 droplets.

Schottman (1978), in a study using single 5-mm drops, described canopy throughfall in terms of direct (drops not intercepted) and indirect (drops intercepted) raindrop penetration. Indirect penetration occurred as splash from leaf surfaces or drips from leaf margins. He showed that a 5-mm drop, after striking an inclined

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TABLE 1. MASS DISTRIBUTION OF THROUGHFALL BY DROP DIAMETER AT TIME = 10 MINS.

Row width, mm	Crop stage, wks	Canopy cover, %	Mean leaf margin elevation, m	Mass fraction of throughfall by drop diameter				Mass fraction of stemflow
				<1.5mm	1.5-4.5mm	4.5-5.5mm	>5.5mm	
500	5	76	0.5	0.02	0.06	0.33	0.11	0.47
	12	77	1.1	0.03	0.06	0.25	0.10	0.57
	15	66	0.9	0.03	0.07	0.40	0.17	0.34
750	5	—*	0.5	0.04	0.12	0.41	0.14	0.30
	12	70	1.1	0.03	0.08	0.27	0.19	0.43
	15	33	0.9	0.04	0.06	0.52	0.21	0.18
Control	—	0		0	0.01	0.86	0.13	0

* Photographs for measuring canopy cover were lost.

foliar surface, did not form a splash crown but was deflected from its original trajectory and left the leaf surface as an unstable, high-energy sheet of water that fractured into small drops 1 mm in diameter or less. Drops striking surfaces inclined more than 30 deg retained more of their original kinetic energy than those striking more horizontal surfaces, and leaf stiffness had little effect on the splash phenomenon. Deformation of the leaf tissue around the impact zone dictated whether a drop was deflected or retained on the leaf surface.

McGregor and Mutchler (1978) found that, although the number of drops per unit area under cotton plants decreased with an increase in canopy cover, median drop sizes were larger under the canopy than in the interrow area and largest at the periphery of the canopy. They showed that the kinetic energy of simulated rainfall was reduced by 95% in some instances under dense cotton canopy and was reduced by 75% over the entire sampled area. Rainfall kinetic energy increased in the middle of the interrow area because of splash from the leaves.

DeTar et al. (1980), to cope with the problem of soil losses from landscaped areas, described the USLE canopy subfactor model in the equation:

$$C_1 = 1 - Pc'' (1 - C_H) \qquad [1]$$

where C_1 is the canopy subfactor, Pc'' is the decimal fraction of the area covered by the canopy, and C_H is the canopy subfactor for 100% canopy over bare, disturbed soil. C_H is a function of the fall height and drop diameter. A field rating system was devised to make C value estimates for a variety of ornamental plants.

METHODS AND PROCEDURES

Characteristics of corn canopy throughfall were measured under simulated rainfall at three stages of crop canopy development and two row spacings. Measurements made included canopy cover, throughfall dropsize, throughfall drop velocity, and throughfall volume.

Experimental Design

Corn was planted in 20-L, soil-filled containers on June 20, 1979, at row spacings of 750 mm and 500 mm and with 305 mm between individual plants (44 000 and 66 000 plants/ha). The plants were grown outdoors in a sheltered environment to protect the plants from wind damage. Rainfall simulation was performed at 5, 12 and 15 wk (vegetal senescence) after emergence. Canopy cover and mean leaf margin elevations are given in Table 1. The same plants were used for the 12- and 15-wk experimental runs. Leaves below the second node were stripped from the stalk before each run to allow the placement of a collection gutter for measurement of canopy throughfall and the insertion of dye paper between the gutter and the lowest leaves during data collection.

Additionally, a control run was made where there was no plant canopy. This control run furnished data on the rainfall, drop size, and drop velocity measurements with which runs involving canopies were compared.

The rainfall simulator used contained eight wedge-shaped applicator tanks with plexiglass bases mounted radially on a 1.4 m diameter octagonal wheel (Mutchler and Moldenhauer, 1963). The drop formers were inserted in the plexiglass base in an epicyclic pattern to achieve a uniform areal distribution when the unit was rotated. A constant head of deionized water was maintained over the drop formers that produced 5-mm diameter drops at an intensity of 72 mm/h. The drop formers were located 6.5 m above the soil surface of the plant containers.

Canopy Cover Measurement

The percentage of the area between rows covered with canopy was measured by using a photographic grid method similar to that of Hartwig and Laflen (1978). Two color slides were taken before and after simulation and averaged to determine the percentage of canopy cover.

Drop Size Measurement

Drop sizes were measured by using a dye-paper technique (Magarvey, 1957). Rectangular sheets of Whatman No. 1 filter paper were trimmed to 750 mm × 125 mm and 500 mm × 125 mm for use under the canopy at the two row spacings. An air brush was used to coat the paper with an emulsion of Sheaffer green ink and ethanol. The emulsion contained 2.5% by volume of ethanol to improve atomization of the dye. After being coated with dye, the treated sheets were stored at approximately 25 °C in a dry atmosphere before being exposed to rainfall. After exposure the sheets were again stored at 25 °C until they were analyzed. After the dye paper was calibrated with drops of known diameter, Magarvey's equation (Magarvey, 1957) was modified to account for differences in the concentration of the dye paper emulsion used in the experiment. A maximum error of 2.7% was estimated between drop size measurements when drops were released from 0.4 m and 6.0 m above the dye paper.

For sampling under canopy, the dye paper sheets were taped to cardboard and exposed for 1 to 3 s. Splashing was minimized by inserting and withdrawing the sheets rapidly and avoiding contact with the leaves or stem. Four sheets were exposed at 10, 30, and 60 min after rainfall simulation began.

Drop stain diameters for drops that fully penetrated the dye paper were measured within 125-mm strips across the row. Stains that bridged adjacent strips on the dye paper were summed within the strip that contained more than half of the surface area of the stain. Stain diameters for irregularly shaped drops were estimated as the average of the diagonals bisecting the longest and shortest diameters of the stain. Very large circular stains were assumed to have formed from the overlapping of stains from a number of drops. In these cases, stain diameter was estimated by completing an external arc on the circumference of the stain to form a circle. Drop stains from four dye paper sheets were measured and averaged for each experiment. Drop size frequencies were determined for each experiment and were reported for each 125-mm row interval between the corn plants.

Drop Velocity Measurement

Drop velocities were measured by a photographic procedure that recorded the raindrop fall distance over a brief time period (Green, 1952). A single-lens-reflex camera with a 200-mm telephoto lens was mounted vertically on a tripod, raised 0.30 m above the soil surface of the potted corn plants. The tripod was erected 3.5 m from the nearest plant and was moved at right angles to the row direction in intervals of 250 mm parallel to the interrow space (twice for the 500-mm spacing, three times for the 750-mm spacing). The tripod was placed at the midpoint of each 250-mm interval to minimize angular distortion of the true distance the drops fell while the camera shutter remained open.

The angle of acceptance of the lens was 12 deg, and the theoretical depth of field at a distance of 3.7 m from the camera was 150 mm. The photographic images remained in acceptable focus 200 mm in front and 100 mm behind a graduated scale placed across the row 3.7 m from the camera. Outside this range the photographic images lost considerable sharpness.

A maximum error of 10% in drop length due to angular distortion of the drop trace by the lens was expected between drops falling on the central axis at the front of the field and those 125 mm from the central axis at the rear of the field (based on a drop falling at 7.4 m/s with a projected length of 173 mm).

Dark field illumination was provided by a 100-W tungsten halogen spotlamp, set at 45 deg to the row and mounted at the camera elevation. Black fabric behind the corn gave a background for the light reflected and refracted by the drops into the focal plane of the camera. At 1/60 s the drop traces appeared as dark lines on the film negative. The film (400 ASA) used in the camera was push-processed with a developer that produced negatives of sharp contrast.

A full-frame film strip projector was used to project the film negatives onto a screen of millimeter graph paper such that the millimeter markings of the projected graduated scale coincided with those of the screen. The vertical components of drop images that were in sharp focus were measured directly from the screen. A correction for the relative motion of the shutter curtain and falling drops was made by subtracting the shutter curtain velocity from the velocities determined from the projected negatives, based on the equation:

$$V = \frac{hy}{t} - 3 \quad [2]$$

where V = fall velocity (m/s), hy = vertical component of drop trace (m), and t = shutter speed (s). The fall velocity (V) is an approximation, however, since the drop continued to accelerate during the 1/60th s it took for the shutter to move across the focal plane.

Drop velocities were determined from 20 film negatives for each 125-mm row interval, and at 10, 30, and 60 min after the start of rainfall simulation.

Volume Measurement of Throughfall

The volume of throughfall that reached the collection gutter was measured and the volume of intercepted rainfall that ran down the plant stalks (stemflow) was calculated for 10-min periods beginning 10, 30, and 60 min after rainfall simulation began. The volume of throughfall was measured for each 125-mm interval across the row.

Stemflow was calculated by subtracting the total volume of water collected from the gutter under canopy from the volume collected during the control experiment. Stemflow collected at the stalks exceded the calculated stemflow since the stalks carried rainfall intercepted over an area larger than the area of the collection gutter.

Estimation of Throughfall Kinetic Energy

Throughfall kinetic energy was calculated for each crop growth stage and row spacing three times during each experimental run by using records of drop size distribution, drop velocity distribution, and the volume distribution of throughfall beneath the crop. Throughfall kinetic energy was calculated separately for each mechanism of penetration (raindrop splash, direct drop penetration, and drops from leaf margins) and then as the sum of the energy components, weighted according to the volume of throughfall collected within each 125-mm row interval over a 10 min period. These values of kinetic energy were then expressed as decimal fractions of the rainfall kinetic energy for each 125-mm row interval in the control experiment. The raindrop size distribution and the volume distribution from the control experiment were combined with the mean fall velocity of 7.4 m/s to obtain the rainfall kinetic energy of the control.

RESULTS AND DISCUSSION

Throughfall Drop Size

Drop size distributions, obtained after analyzing the exposed dye sheets for each 125-mm row interval and averaging the results over four subsamples, showed that the throughfall contained large numbers of drops less than 1.5 mm in diameter. These drops represented only 3% ± 0.3% of the total rainfall mass within each row interval for each experimental crop 10 min after rainfall simulation began (Table 1). All drops of 1.5-mm diameter or less recorded during an experiment were assumed to have splashed from leaf surfaces. Kitanosono (1972) and Schottman (1978) confirmed that large numbers of drops not larger than 1.5 mm in diameter are the product of a collision between a drop and a leaf

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For sampling under canopy, the dye paper sheets were

TABLE 3. DISTRIBUTION OF THROUGHFALL MASS AND KINETIC ENERGY (FRACTION OF CONTROL) ACROSS A ROW, AVERAGE OF THREE TIMES

Row width, mm	Crop stage, wks	Canopy cover, %	Distance from row, mm						Mass fraction of stemflow	Fraction of throughfall mass or kinetic energy
			0-125	125-250	250-375*	375-250*	250-125	125-0		
					Mass, fraction of control total					
500	5	78	0.21	0.09	—	—	0.12	0.11	0.46	0.54
	12	76	0.11	0.15	—	—	0.14	0.11	0.49	0.51
	15	67	0.14	0.20	—	—	0.17	0.17	0.31	0.69
Control	—	0	0.27	0.24	—	—	0.24	0.25	0.00	1.00
750	5	—†	0.10	0.11	0.17	0.14	0.10	0.10	0.28	0.72
	12	72	0.07	0.18	0.15	0.08	0.08	0.07	0.38	0.62
	15	36	0.11	0.19	0.16	0.14	0.13	0.12	0.16	0.84
Control	—	0	0.16	0.18	0.16	0.16	0.17	0.16	0.00	1.00
					Kinetic energy, fraction of control total					
500	5	78	0.12	0.06	—	—	0.12	0.08		0.38
	12	76	0.08	0.11	—	—	0.11	0.09		0.40
	15	67	0.10	0.15	—	—	0.14	0.12		0.50
Control	—	0	0.27	0.24	—	—	0.24	0.25		1.00
750	5	—†	0.07	0.08	0.11	0.12	0.08	0.06		0.51
	12	72	0.04	0.11	0.09	0.06	0.06	0.05		0.41
	15	36	0.08	0.13	0.13	0.12	0.10	0.10		0.66
Control	—	0	0.16	0.18	0.16	0.16	0.17	0.16		1.00

* Since distances from row are column headings, for 500-mm row widths there will be no values for these columns.
† Photographs for measuring canopy cover were lost.

throughfall volume was generally lowest near the plant where the crop cover was greatest.

The simulated rainfall that did not penetrate corn canopy either directly or indirectly was intercepted and traveled down the corn stalk as stemflow. Stemflow was highly correlated with average canopy cover (canopy cover averaged over the entire rowspace) and decreased with rainfall duration as leaves became heavier and adopted a more vertical orientation within the canopy, thus conducting less water to the basal part of the leaf. Stemflow ranged from 49% under the 12-wk, 500-mm row width canopy to 16% under the senesced canopy at a 750-mm row width. In instances where high stemflow occurred, the assumption that the increase in throughfall erosivity due to coalesced drops falling from leaf margins offsets the energy lost through stemflow may lead to overestimation of throughfall erosivity, although it did not do so in this study.

Throughfall Kinetic Energy

Because of the stochastic nature of the drop velocity data and the evidence of decreasing data frequency from left to right across the crop row due to lighting, the drop velocity data were not considered as reliable as the drop size distribution data for calculating the fraction contribution to total (throughfall) kinetic energy by the three mechanisms of canopy throughfall—direct penetration, splash, and drips from leaf margins. The kinetic energies of each mechanism of throughfall were calculated by summing the mass fraction of drops within each drop diameter classification (Table 1) and multiplying by the square of the appropriate average fall velocity. These components were added and then multiplied by a factor M_C/M_T to eliminate discrepancies between dye paper sampling times and to correct for sampling bias across the row for each row interval and run (equation [3]).

$$KE = 0.5 \frac{M_C}{M_T} [\Sigma MV^2 \text{ (splash)} + \Sigma MV^2 \text{ (direct penetration)} + \Sigma MV^2 \text{ (leaf margin drip)}] \quad [3]$$

where

KE = throughfall kinetic energy for a specific mm row interval

M = drop mass fraction of each drop diameter category falling within a specific 125-mm row interval

V = mean drop velocity for a particular throughfall mechanism within a specific 125-mm row interval

M_C = mass of throughfall within a 125-mm row interval collected during a run

M_T = total mass of rainfall collected under the canopy during a run

The control rainfall kinetic energy was obtained by using the volume distribution across the row during the control experiment (expressed as a fraction of the total) and the mean terminal velocity of the simulated rainfall.

Throughfall kinetic energies, as a fraction of the total kinetic energy for the control, are given by distances from the row in Table 3. For the 500-mm row width, canopy reduced rainfall erosivity an average of 57% as compared with an average of 47% for the 750-mm row width. Kinetic energy under a canopy was slightly lower in the 0 to 125 interval nearest the plant.

Throughfall kinetic energy, when calculated for each 125 mm interval across the crop row, was well correlated with canopy cover ($r = -0.85$). This was anticipated since directly penetrating drops accounted for between 68% and 93% of total throughfall kinetic energy. Leaf margin drops represented as much as 31% of the total within a single row interval (12 wk, 750 mm crop, 125 mm each side of row middle) and as such could pose an erosion hazard, which might not be explained by canopy cover. Averaging the effect of indirect penetration by leaf margin drips across the row space may underestimate the contribution made by this mechanism to erosion, especially since the drops are often concentrated within a small impact area. Partitioning the interrow area into subareas of differential interrill erosion might improve estimation of soil loss under canopy.

Raindrop splash accounts for only 1% to 2% of the

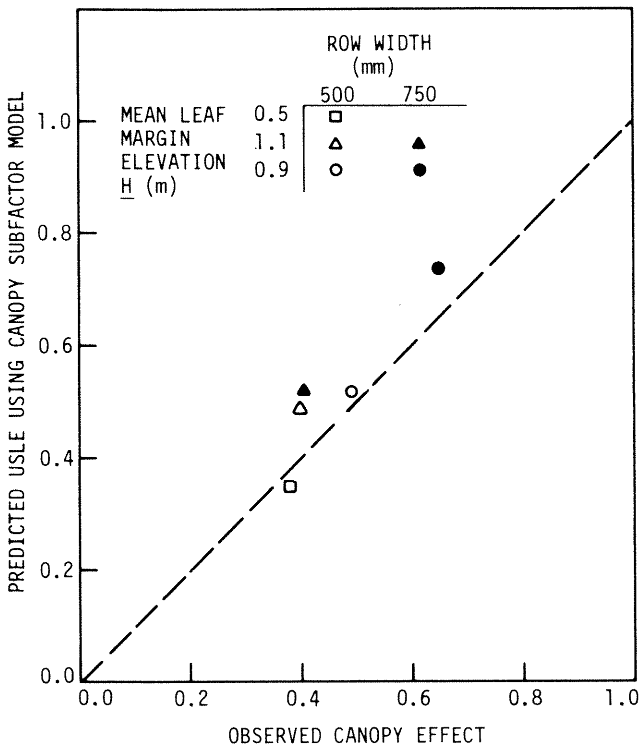

Fig. 1—A comparison of the measured ratio of kinetic energy under a corn canopy to kinetic energy above a corn canopy to that predicted using the USLE canopy subfactor model.

kinetic energy of throughfall; splashed drops are diffuse in their distribution on the soil surface and as such do not present an erosion hazard.

Comparison with USLE Canopy Subfactor Model

The effect of corn canopy on throughfall kinetic energy is compared with that of the USLE canopy subfactor model in Fig. 1. The data are separated by row spacing and the mean elevation of the leaf margin.

The observed canopy effect and that predicted by the USLE subfactor model showed good agreement. As shown in Fig. 1, the data covered an appreciable range, and, although the number of data were quite limited, the good comparisons lend confidence to the use of the canopy subfactor model in the USLE, at least for corn.

SUMMARY AND CONCLUSIONS

The effects of corn canopy on the size and velocity of raindrops passing through a corn canopy (throughfall) were studied in a rainfall simulation experiment. The kinetic energy of throughfall relative to the kinetic energy of the simulated rainfall without a crop was compared for various row spacings, crop stages, and positions within the row.

Throughfall kinetic energy was highly correlated with canopy cover, since drops directly penetrating the crop canopy accounted for much of throughfall kinetic energy. However, drops from leaf margins amounted to 31% of throughfall kinetic energy in a central row position for a wide spaced 12 wk canopy. Coalesced drops concentrated within a small impact area could lead to higher soil losses under tall crops.

We found little difference between throughfall kinetic energy predicted by the USLE canopy subfactor model and those measured in this experiment even though a considerable range in canopy heights and canopy covers was experienced. Although the experimental values of throughfall kinetic energy for a given canopy were near those predicted by the USLE canopy subfactor model, the importance of drops falling from leaf margins as elements of throughfall erosivity, might increase outdoors where raindrops are smaller than the drops from the simulated rainfall used for this experiment.

Stemflow accounted for as much as 49% of the total incident rainfall. It was highly correlated with average canopy cover and decreased with the duration of rainfall. Where high stemflow occurs, the USLE canopy subfactor model assumption that an increase in throughfall erosivity due to an increase in the size of drops from leaf margins offsets the energy lost through stemflow might not be valid for all crops and could lead to an error in estimation of throughfall erosivity. The fact that the predicted and observed values of throughfall erosivity were quite similar, despite large stemflows, underlines the importance of coalesced drops as agents of throughfall erosivity.

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